Decoherence in Josephson Qubits from Junction Resonances

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Although Josephson-junction qubits show great promise for quantum computing, the origin of dominant decoherence mechanisms remains unknown. We report Rabi oscillations for a phase qubit, and show that their "coherence amplitude" is significantly degraded by spurious microwave resonances. These resonances appear to arise from changes in the junction critical current, produced by fluctuations in the position of electrons or atoms within the tunnel barrier. We argue this mechanism is a dominant source of decoherence in all present Josephson qubits, and improvements will require materials research directed at the tunnel barriers to eliminate these spurious resonances.

Josephson junctions are good candidates for quantum computing[1], with recent experiments demonstrating reasonably long coherence times, state preparation, manipulation, and measurement, and the coupling of qubits for eventual gate operations[2–7]. Josephson quantum bits (qubits) may be considered as non-linear "LC" resonators formed by the Josephson inductance and capacitance of a tunnel junction[4]. Making qubits from such electrical elements is advantageous because coupling of qubits and scaling to large numbers should be relatively straightforward using integrated-circuit fabrication technology. However, electrical circuits may also couple to unwanted electromagnetic modes, producing decoherence. Ultimately, all possible decoherence mechanisms must be investigated and understood in detail.

Here we report the discovery of a new decoherence mechanism that arises from spurious microwave resonances. Although previous reports have focused on the characteristic decay *time* of coherent oscillations, our data demonstrates that decoherence from these spurious resonances primarily affects the *amplitude* of the oscillations. We propose a model that explains these resonances as being produced by fluctuations in the tunnel barrier, and connect this phenomena with previous measurements of both junction current-voltage characteristics and 1/f critical-current noise. Because these spurious resonances appear to be a major source of decoherence in all present Josephson qubits, they must be understood and eliminated to enable building a Josephson quantum computer.

The circuit used in this experiment is shown in Fig. 1(a). The junction is isolated from dissipation of the leads in a similar manner to a phase qubit described previously[4]. The circuit has been improved by placing the junction in a superconducting loop of inductance L to minimize the voltage and thus the generation of quasiparticles and self-heating when the qubit state is measured[8]. The junction is biased with current I close to the critical current I_0 by coupling magnetic flux through a transformer with mutual inductance M. As shown in Fig. 1(b), the qubit states are formed in a cubic

potential of the left well and are measured by tunneling to states in the right well. Tunneling to the right well changes the flux through the loop by $\sim \Phi_0 = h/2e$, which is easily read-out with a pulsed critical-current measurement in a separate SQUID detector. The qubit was fabricated using aluminum metallization, with an aluminum-oxide tunnel barrier formed by thermal oxidation[8].

The $0 \to 1$ qubit transition frequency ω_{10} is measured spectroscopically[9], as shown in Fig. 2(a). For our measurements, the current bias is pulsed for a time $\sim 50\,\mu s$ to a value close enough to the critical current so that approximately $3 - 4$ energy levels are in the cubic well. Transition frequencies are probed by applying microwave current $I_{\mu w}$ at frequency ω and measuring a resonant increase in the net tunneling probability. We observe in Fig. 2(a) a decrease in the transition frequency as the
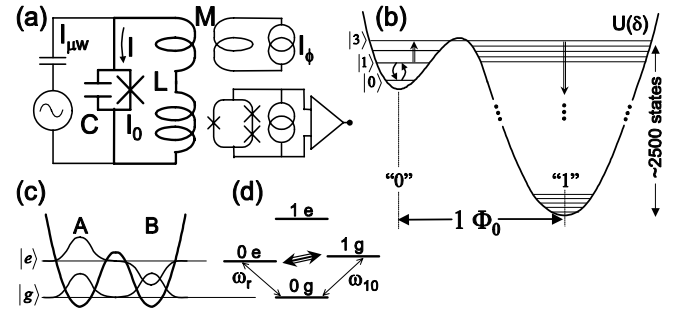

FIG. 1: (a) Circuit diagram for the Josephson junction qubit. Junction current bias I is set by I_ϕ and microwave source $I_{\mu w}$. Parameters are $I_0 \simeq 11.659\,\mu A$, $C \simeq 1.2\,pF$, $L \simeq 168\,pH$, and $L/M \simeq 81$. (b) Potential energy diagram of qubit, showing qubit states $|0\rangle$ and $|1\rangle$ in cubic well at left. Measurement of $|1\rangle$ state performed by driving the $1 \to 3$ transition, tunneling to right well, then relaxation of state to bottom of right well. Post-measurement classical states "0" and "1" differ in flux by Φ_0, which is readily measured by readout SQUID. (c) Schematic description of tunnel-barrier states A and B in a symmetric well. Tunneling between states produces ground $|g\rangle$ and excited $|e\rangle$ states separated in energy by $\hbar\omega_r$. (d) Energy-level diagram for coupled qubit and resonant states for $\omega_{10} \simeq \omega_r$. Coupling strength between states $|1g\rangle$ and $|0e\rangle$ is given by $\tilde{H}_{int}$.

bias current approaches the critical current, as expected theoretically for the ω_{10} transition.

Additionally, we observe a number of small spurious resonances (indicated by dotted vertical lines) that are characteristic of energy-level repulsion predicted for a coupled two-state system. These extra resonances have a distribution in splitting size, with the largest ones giving a splitting of $\sim 25\,$MHz and an approximate density of 1 spurious resonance per $\sim 60\,$MHz.

We observed coherent "Rabi oscillations" between the $|0\rangle$ and $|1\rangle$ state by pulsing microwaves at the $0 \rightarrow 1$ transition frequency ω_{10}, then measuring the occupation probability of state $|1\rangle$ by applying a second microw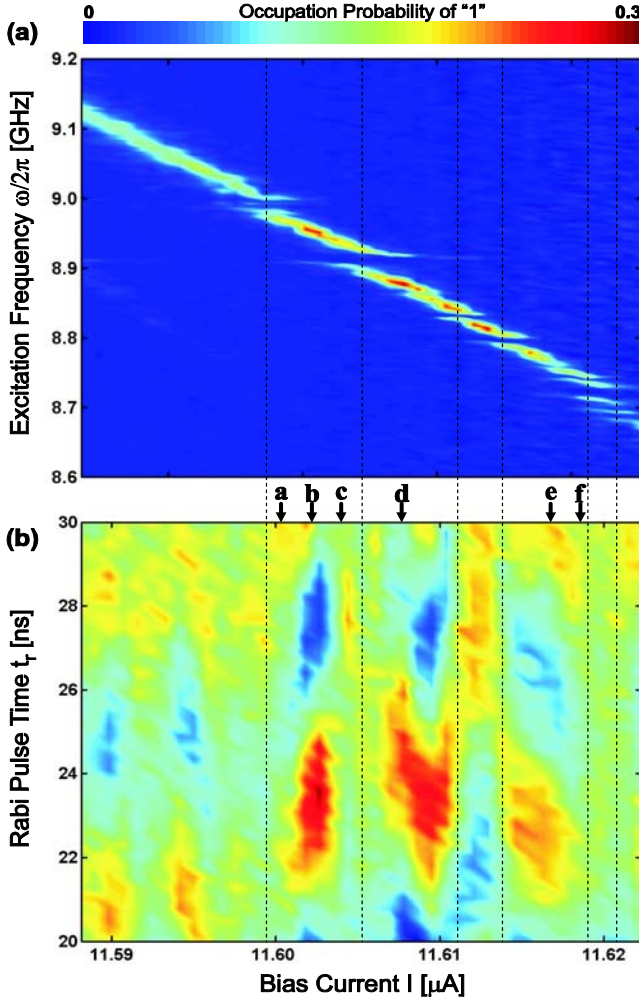ave pulse resonant with the $1 \rightarrow 3$ transition frequency ω_{31}[4]. Figure 3(a)-(c) shows for three values of microwave power the occupation probability versus the pulse width t_r. The decay of the oscillations is approximately exponential and gives a coherence time of $41\,$ns. Figure 3(d) shows that the oscillation frequency is proportional to the microwave amplitude, as expected.

The correlation between Rabi oscillations and spurious resonances is demonstrated in Fig. 2. For the data in Fig. 2(b), the microwave frequencies of the Rabi and measurement pulses were adjusted with I to center on the transition frequencies obtained from spectroscopy data. We observe that the oscillation amplitude, represented by a variation in color, is suppressed over time (vertical axis) at particular bias currents (horizontal axis). The dashed vertical lines show that this suppression is correlated to those transition frequencies ω_{10} where there are pronounced resonance structures. It is clear that these spurious resonances strongly disrupt the Rabi oscillations.

In Fig. 4 we show the decay of the Rabi oscillations as the bias is moved through spurious resonances. Near resonances we find unusual behavior such as beating (b) and even recovery of the oscillations with time (c). The general trend is that a spurious resonance causes loss in coherence not by a decrease in the decay time of the oscillations, but by a decrease in the amplitude of the oscillations.

The maximum amplitude of our Rabi oscillations is approximately $30\,\%$, which is significantly less than unity. Experimental checks indicate this low amplitude is intrinsic to the qubit[10]. Because the spurious resonances are observed to be randomly distributed in size and frequency, any bias point is probably always near at least a few small resonances. As happens for the major res-
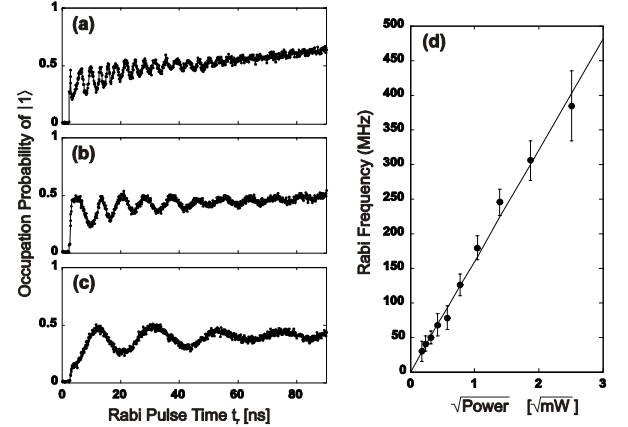

FIG. 2: (a) Measured probability of state "1" versus microwave excitation frequency $\omega/2\pi$ and bias current I for a fixed microwave power. Data indicate ω_{10} transition frequency. Dotted vertical lines are centered at spurious resonances. (b) Measured occupation probability of $|1\rangle$ versus Rabi-pulse time t_r and bias current I. In panel (b), a color change from dark blue to red corresponds to a probability change of 0.4. Color modulation in time t_r (vertical direction) indicates Rabi oscillations.

FIG. 3: (a)-(c) Measured occupation probability of $|1\rangle$ versus time duration of Rabi pulse t_r for three values of microwave power, taken at bias $I = 11.609\,\mu$A in Fig. 2. The applied microwave power for (a), (b), and (c) correspond to 0.1, 0.33, and $1.1\,$mW, respectively. (d) Plot of Rabi oscillation frequency versus microwave amplitude. A linear dependence is observed, as expected from theory.

onances, these small resonances each degrade the coherence amplitude, so that the net amplitude is reduced.

Previous experiments have also observed spurious resonances[11], with Rabi oscillation data reported only for maximum coherence. Table I lists the coherence time and amplitude of Rabi oscillations for several experiments[12], which all show a reduced amplitude.

We have observed that the frequencies and magnitudes of our spurious resonances occasionally change in time while the device is cold, as well as when thermally cycled to room temperature. This behavior indicates that at least some resonances are microscopic in origin, as opposed to resonances from, for example, harmonic oscillator modes from the leads of the device.

We have constructed a model for the microscopic resonances that we believe can explain their magnitude and density. The model is related to that describing 1/f fluctuations in the critical current of the junction[13, 14], except we consider two-level states in the barrier with large tunneling matrix elements corresponding to a microwave frequency[15]. If we consider two states in the tunnel barrier that have configurations A and B producing critical currents I_{0A} and I_{0B}, then the interaction Hamiltonian between the resonance and the critical current is

$$H_{int} = - \frac{I_{0A}\Phi_0}{2\pi} \cos\widehat{\delta} \otimes |\Psi_A\rangle \langle\Psi_A|$$
$$- \frac{I_{0B}\Phi_0}{2\pi} \cos\widehat{\delta} \otimes |\Psi_B\rangle \langle\Psi_B| \ ,$$

where $\widehat{\delta}$ is an operator corresponding to the phase difference across the junction, and $\Psi_{A,B}$ describe the two wave functions for the two configuration states within the tunnel barrier. If we assume a symmetric potential
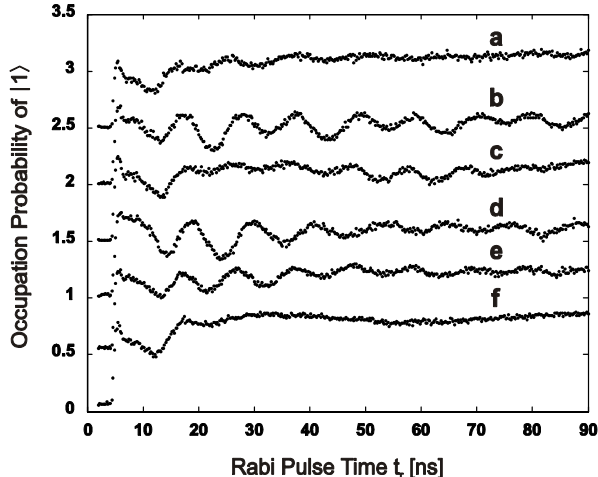

FIG. 4: Measured occupation probability of $|1\rangle$ versus time duration of Rabi pulse t_r for current biases a-f as noted by arrows in Fig. 2. Data a-e is offset for clarity. Note that when the bias is changed, the coherence is degraded mainly as a loss in amplitude, not by a decrease in coherence time.

with energy eigenstates separated by $\hbar\omega_r$, the ground and excited states are given by $|g\rangle \simeq (|\Psi_A\rangle + |\Psi_B\rangle)/\sqrt{2}$ and $|e\rangle \simeq (|\Psi_A\rangle - |\Psi_B\rangle)/\sqrt{2}$. Using matrix elements for $\cos\widehat{\delta}$ appropriate for the phase qubit[16] and including only the dominant resonant terms arising from this interaction Hamiltonian, we find

$$\widetilde{H}_{int} = \frac{\Delta I_0}{2} \sqrt{\frac{\hbar}{2\omega_{10}C}} \left(|0\rangle\langle 1| \otimes |e\rangle\langle g| + |1\rangle\langle 0| \otimes |g\rangle\langle e|\right) \ ,$$

where $\Delta I_0 = I_{0A} - I_{0B}$. Figure 1(d) shows an energy level diagram for the case where $\omega_r \approx \omega_{10}$. The coupling of the two intermediate energy levels through $\widetilde{H}_{int}$ produces a repulsion in the energy eigenstates that corresponds to the spectroscopic data in Fig. 2(a). From the magnitude of the level repulsions at resonance $2|\widetilde{H}_{int}|/h \simeq 25\,\mathrm{MHz}$, we obtain from our model $\Delta I_0 \simeq 65 \cdot 10^{-6} I_0$.

This magnitude of ΔI_0 is consistent with a description of the tunnel junction whose parameters are obtained from current-voltage characteristics. To account for a non-uniform tunnel barrier, we use a mesoscopic theory[17] to predict the Josephson and quasiparticle currents, where the currents are carried by independent conduction channels of tunnel transmission τ_i. These transmission coefficients can be measured[18] from steps in the quasiparticle current of magnitude $2/\tau_i$ that arises from n^{th} order multiple Andreev reflections at voltages $2\Delta/n$. If we assume the current is carried by only N_{ch} channels, each with transmission τ, then our measured current-voltage characteristics[8] imply $\tau \approx 4 \cdot 10^{-3}$ for a critical-current density of $\sim 40\,\mathrm{A/cm^2}$. For our $32\,\mu\mathrm{m}^2$ qubit junction with a nomal-state resistance $R_N = 29\,\Omega$, we calculate $N_{ch} = h/2e^2 R_N \tau \simeq 1.3 \cdot 10^5$, which implies a channel density of $4 \cdot 10^3/\mu\mathrm{m}^2 = 1/(16\,\mathrm{nm})^2$. This simple model implies that $N_{ch}(\Delta I_0/I_0) \simeq 8$ channels are switched on and off between the junction states A and B. Because tunnel junctions typically have a distribution of transmissions and our spectroscopy measurement picks out the largest resonances, it seems likely that magnitude of ΔI_0 is explained by resonances formed from single conduction channels of magnitude $\tau_i \approx 2 \cdot 10^{-2}$.

Since the physical model of these microwave resonances is similar to that describing 1/f critical-current noise at

Reference	Junction	Coh. Time	Coh. Ampl. (%)
[5]	Al/AlOx/Al	150 ns	50
[2]	Al/AlOx/Al	1 μs	(30)
[4]	NbAl/AlOx/Nb	20 ns	15
[3]	NbN/AlN/NbN	4.9 μs	(1)
this work	Al/AlOx/Al	41 ns	30

TABLE I: Table of coherence time and amplitude of Rabi oscillations for several previous experiments. All data show a coherence amplitude smaller than unity. Materials for the tunnel junction electrodes and barrier are also listed. Values in parentheses are estimated[12] from published data.

audio frequencies, it is useful to compare these data. Measurements on submicrometer Josephson junctions have shown discrete changes in the junction critical current from individual fluctuators[13, 14, 19]. For an aluminum junction with area $0.08\,\mu m^2$, a recent experiment has reported a change in critical current of $\Delta I_0 \simeq 10^{-4} I_0$ for a single fluctuator[14]. Assuming this fluctuator turns a channel on and off, these data imply an areal density of fluctuators $N_{ch}/\mu m^2 \sim 1.25 \cdot 10^5$, about 30 times greater than the channel density $4 \cdot 10^3/\mu m^2$ that we have obtained from our microwave resonance data. Additionally, the density of fluctuators in frequency may also be estimated from previous experiments. Several experiments give approximately one resonance per decade in frequency for junctions with area $0.1\,\mu m^2$[13, 14], which is higher by only a factor of 2 than the areal density we observed for the resonances at microwave frequencies.

The magnitude and density in frequency of the microwave resonators and 1/f noise fluctuators are in reasonable agreement, especially since they compare phenomena that have characteristic frequencies separated by many orders of magnitude. With good agreement of the fluctuator model, our data, and data from 1/f noise, we propose a strong connection between decoherence caused by spurious resonances and 1/f noise. These two phenomenon probably originate from the same microscopic behavior within the tunnel barrier.

The connection of decoherence and 1/f noise is useful because previous measurements of the magnitude of 1/f critical current noise can be used to propose new alternatives to the fabrication of Josephson qubits. A recent compilation of 1/f noise data indicates that tunnel junctions made from oxides of Al, Nb, and PbIn all have similar magnitudes of noise[14]. This evidence suggests that alternatives to thermal or plasma oxidation of metals should be investigated to fabricate tunnel barriers. We also conjecture that the very low density of conductance channels may indicate that tunneling channels are located at defects in the tunnel barrier[20], which unfortunately is a likely location for two-level fluctuators or resonators.

In conclusion, we have demonstrated that spurious microwave resonances in our Josephson junction qubit primarily alter Rabi oscillations by reducing their "coherence amplitude". These resonances can be understood as arising from two-level fluctuators within the tunnel barrier, which couple to the qubits states through the critical current. Increasing the coherence of all Josephson qubits will require materials research directed at improving tunnel barriers.

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[11] In Ref. [5], the resonance near the degeneracy point is potentially a spurious resonance. In Ref. [2], a spurious resonance was observed in an initial cooldown of the qubit. In a subsequent cooldown the resonance disappeared and good coherence was observed (M. Devoret, private communication).

[12] The coherence amplitude of [2] was increased by a factor of 2 to account for reduced fidelity of measurement. The coherence amplitude of [3] was estimated assuming a full coherence signal would modulate by $\Gamma_1/\Gamma_0 \simeq 1000$.

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